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# INSULATION COORDINATION AND FAILURE MITIGATION CONCERNS FOR ROBUST DC ELECTRICAL POWER SYSTEMS (PREPRINT)


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**14. ABSTRACT**
The current trend in modern electrical power systems for terrestrial and aerospace applications is to utilize dc at voltages well above the traditional levels of 12 to 42 Vdc. New airborne systems contain numerous uses of 270 Vdc, and bipolar systems with a 540 V differential are likely to appear in the near future. The use of high dc potentials create flash-over and arcing risks that are much more problematic than the traditional ac or low-voltage dc. Low-pressures experienced in aerospace environments exacerbate the dangers. Traditional overcurrent protective devices may be too slow to mitigate damage caused by high current arcing. Likewise, the extinction of a low current, impedance-limited dc arc may require active power removal since there is no natural zero-crossing. Achieving robustness in high-voltage dc power systems, then, requires adequate insulation design criteria and reliable failure mitigation. Some design specifications and guidelines will be reviewed and shortcomings identified. Even with technically sound designs, absolute elimination of flashover and arcing cannot be assured in realistic environments as systems age. Hence, critical systems will require detection and mitigation strategies to prevent catastrophic consequences.

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# Insulation Coordination and Failure Mitigation Concerns for Robust Dc Electrical Power Systems

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## Abstract

**The current trend in modern electrical power systems for terrestrial and aerospace applications is to utilize dc at voltages well above the traditional levels of 12 to 42 Vdc. New airborne systems contain numerous uses of 270 Vdc, and bipolar systems with a 540 V differential are likely to appear in the near future. Plug-in electric vehicle and solar applications typically operate near 350 Vdc. New data server centers are considering distribution voltages up to 380 Vdc. The use of high dc potentials create flash-over and arcing risks that are much more problematic than the traditional ac or low-voltage dc. Low-pressures experienced in aerospace environments exacerbate the dangers. Traditional overcurrent protective devices may be too slow to mitigate damage caused by high current arcing. Likewise, the extinction of a low current, impedance-limited dc arc may require active power removal since there is no natural zero-crossing. Achieving robustness in high-voltage dc power systems, then, requires adequate insulation design criteria and reliable failure mitigation. Some design specifications and guidelines will be reviewed and shortcomings identified. Even with technically sound designs, absolute elimination of flashover and arcing cannot be assured in realistic environments as systems age. Hence, critical systems will require detection and mitigation strategies to prevent catastrophic consequences.**

## 1. Introduction

There has been a relatively recent proliferation of dc power systems operating at voltages that are significantly higher than the traditional 12, 28, and 42 Vdc. Present applications are more numerous than in previous years because significant advances in solid-state switching technology have resulted in the economic feasibility of high-power dc systems. Traditionally, power was transmitted in ac mode in order to take advantage of transformers for voltage-level conversion. Modern switching electronics have allowed voltage-level changes via economical dc-dc converters, and have produced the ability to create light, powerful and controllable motors through dc brushless technology.

Unfortunately, some complications are created by the presence of high voltage dc. Although unwanted insulation breakdown can cause complications in many cases, it is much more problematic for dc systems because of the absence of periodic voltage reversals that are present in more-traditional ac distribution. Arcing can continue undetected for a significant time in dc systems. Also, popular schemes for detection of insulation breakdown—particularly arcing—often look for current switching as the ac current periodically reverses through zero, but this characteristic is absent in a dc system because the natural circuit operation is for current to always remain above (or below) zero.

Among applications that present serious safety concerns are aircraft electrical power systems, distributed (rooftop) solar systems, and electrical ground vehicles. Insulation breakdown resulting in incapacitation of a control system could be catastrophic to aircraft operation and even to ground-vehicle safety. An electrically initiated fire could likely have disastrous consequences for both airborne and terrestrial applications.

Of primary interest for the discussion here are dc applications that have proliferated because of the somewhat recent advances in power-related technology. Voltages are < 1000 Vdc and currents <150 A. For these applications, the primary insulation that is vulnerable to failure is air. This could be a discharge through an air medium or along an air/surface interface.

Achieving robustness in dc power systems requires consistent insulation system design of components and sub-assemblies and, for critical applications, reliable failure mitigation. Future aging of distribution equipment and system components present additional design challenges.

Relevant standards, guidelines, and arc failure-detection methods are briefly discussed below. Most documents are applicable to terrestrial applications where air pressure does not vary significantly from sea-level pressures. Elevated altitudes where aircraft operate, however, require adjustments to sea-level-related specifications because of the reduction of breakdown potentials at reduced pressures.

## 2. Design Standards

A review of standards for design of air-insulated equipment was conducted in [1] with emphasis on application to aerospace environments. Figure 1 illustrates the disparity among published guidelines. Of those reviewed [2-9], IEC 60664 (both -1 and -5) was considered most relevant as a design guide because of its inclusion of a reasonable range of altitudes. For design of printed circuit boards, IPC-2221A was also considered important because of its treatment of material properties and surface contamination.

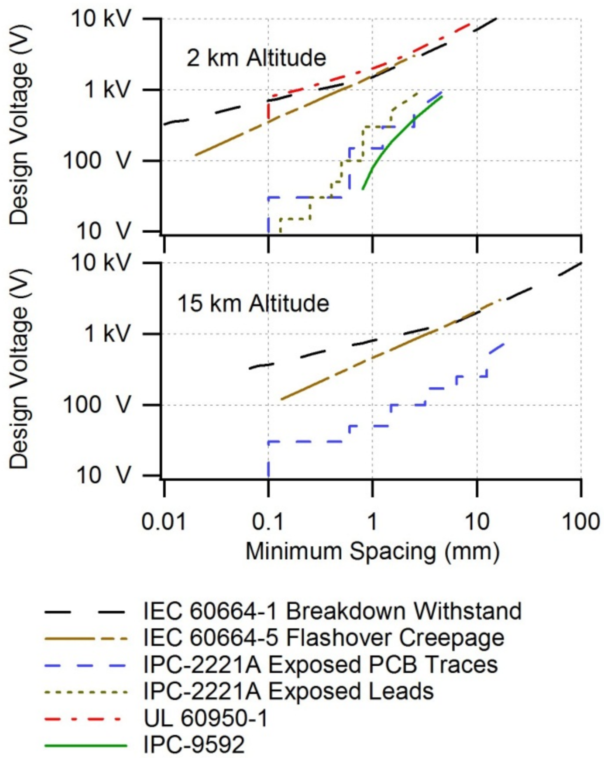


**Figure 1.** Withstand and operating voltages vs. minimum clearance as defined in standards relevant to airborne applications [1].

## 3. Failure Mitigation

Successful efforts in designing for zero occurrences of breakdown (arcing) would include significant safety margins that are generally not practical because of excess size and weight, especially in vehicle and aerospace applications. Even if heroic measures are taken in the design process, defects in manufacturing and maintenance cannot be totally eliminated. Aging issues also present uncertainties in dependability. If potential faults could result in critical safety or reliability concerns, some means of detecting arcing, and mitigating damage is necessary.

An unwanted occurrence of arcing in a power system is generally referred to as an "arc fault." Typically, arcs are characterized as "parallel" or "series," depending upon their circuit location. Circuit paths of parallel arc faults (sometimes referred to as "bolted" faults) typically contain little electrical impedance; current can increase rapidly and reach very high levels. Because damage can be rapid, mitigation should be swift. Whether the power system is ac or dc, the low circuit impedance generally results in fault currents far exceeding the circuit's normal load protective device ratings, resulting in "instantaneous" trips. Just how "instantaneous" depends upon the opening switch characteristic (mechanical or solid-state) in the protective device.

Series arcs (sometimes referred to as "simmering" or "sputtering" arcs) are discharges that are most commonly located in series with the intended load; the electrical impedance of the load limits the current to values that will not trip a conventional fuse or circuit breaker. In practice, any arc with a high circuit impedance to its ground or return path, which limits the fault current to levels below the trip setting of the circuit overcurrent protective device, can be considered a "series" arc fault. Damage resulting from a series arc usually does not occur so rapidly as that resulting from a parallel arc; however, because the series arc may continue for a significant period of time without detection, it may cause significant damage. In high power dc systems, a device that detects and arrests series arcs would be particularly valuable for circuits that cannot easily be visually inspected.

Numerous technologies have been used to detect an arcing event. Non-electrical methods include 1) chemical detection of arc products, 2) thermal detection of a hot arcing site, 3) optical detection of visible emission, and 4) acoustic detection of a pressure wave created by an arc. Chemical and thermal techniques are slow and generally indicate degrees of deterioration. Although optical and acoustic methods may be relatively rapid, they are susceptible to interference and require a degree of access to the arcing site that is often difficult to achieve.

Electrical arc-detection techniques can be rapid and sensitive. Although RF emission can be copious, very little interest has been shown in utilizing the radiative properties of an arc in situations other than open-air power distribution because detection is critically dependent upon the relative position of the source and sensing antenna. Electrical detection is generally limited to voltage and current measurements. In practice, current measurements in the

subsystem wiring or circuits to be protected are usually the most practical.

Typical current and voltage characteristics are shown in Figure 2. Prior to the arc, circuit conditions were 300 Vdc, 24.5 A resistive; electrical noise consisted primarily of line frequencies. Upon separation of series contacts, approximately 15 V was dropped at the arc gap. As the gap widened, arc voltage increased and current decreased. In general, voltage-current characteristics of an arc are physical phenomenon dependent upon (1) constituents in the gas phase, (2) gas pressure, (3) material in contact with the arc, and (4) gap distance.

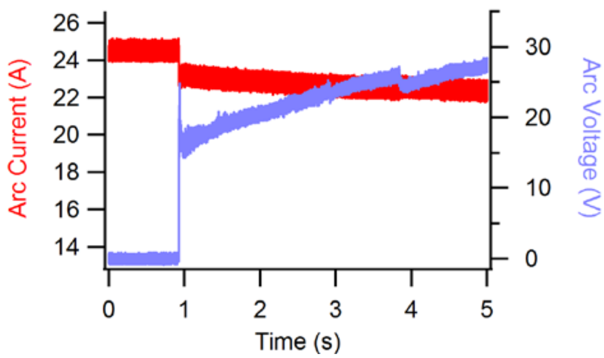


Figure 2. Current and Voltage of a typical drawn arc.

Electrical current-detection methods can be (1) in the time domain such as monitoring for symptomatic current bursts, (2) in the frequency domain such as selective filtering or FFT analysis, or (3) in a time-frequency domain such as wavelet analysis or application of a short-time Fourier transform (STFT). Wavelet and STFT analysis require extensive processing capabilities and their practicality has been demonstrated only in post-processing applications.

Reliable real-time detection, however, is not straightforward. Simple methods include monitoring for higher than normal amplitude peaks or for a predetermined rate of unexpected amplitude bursts. Slightly more complicated are methods of monitoring for power bursts or non-repeatability of power waveform. Most time-domain techniques are based upon a sudden onset of arc current and suffer from confusion with loads that also cause fast current surges.

Non-linearity characteristics have been applied in ac systems. Their success, however, is not universal because the current-voltage characteristic of an arc is frequency dependent. At low frequencies near dc, differential negative conductivity is exhibited where a decrease in current is accompanied by an increase in voltage. At high frequencies, there is a near-linear response of current and voltage [10,11].

A significant number of patents utilize frequency-domain techniques such as monitoring for bursts at selected frequencies via filter or fast Fourier transform (FFT) or, more commonly, monitoring for a broad band of frequencies. A recent improvement is monitoring for a characteristic frequency roll-off [12].

Successful series arc detection in dc systems may include both time-domain and frequency-domain analysis. A simple example would be bursts of broadband frequency content that is not synchronous with loads. No universal technique applicable to dc has yet been published and successfully demonstrated.

Successful bolted-fault protection remains a challenge. Because of rapid growth of current, a significant amount of power can be dissipated in the vicinity of the arc. This includes damage to neighboring wires and structures. Catastrophic results could occur in cases of breached fuel or hydraulic lines leading to explosive consequences.

It will be necessary to rapidly detect and ameliorate a high-current bolted fault. A fast $i^2t$ (current squared x time) detection algorithm may be sufficiently rapid but it is necessary that the current be terminated—or sufficiently reduced—before significant power is expended. It will likely be necessary that solid-state breaker systems be utilized; mechanical breakers are limited in speed of response.

Currently the standards to address, “What determines arc-fault protection and how do you test for it?” are being developed for various terrestrial and vehicular applications. SAE International has addressed arc fault detection for ac power in aircraft [13] and is in the process of addressing dc power applications [14].

## 4. Component Testing

One common quality test of aircraft components, particularly those used at voltages > 1000 V, is detection and measurement of partial-discharge (PD) activity. The presence of PD in a component typically indicates defect sites, and the extent of PD activity can be indicative of the level of deterioration. The reliable performance of the electric-power-system components and subassemblies of such vehicles under sub-atmospheric operating conditions is essential to in-flight reliability and vehicle longevity. Therefore, characterization of the performance and behavior of the electrical insulation in such equipment during exposure to low-pressure environments is extremely important.

International standards address measurement techniques for partial discharges in power components, e.g., IEC 60270 [15]. However, these standards are developed for terrestrial,

atmospheric conditions. Sub-atmospheric pressures found at high altitude can change the temporal nature of the partial discharge event. Hence, guidelines have been developed for partial discharge measurements on components which need to be evaluated at sub-atmospheric pressures for aerospace applications [16].

As the use of dc-fed, power-electronic converters increases, voltage spikes above the nominal supply voltage levels are likely occurrences. This is especially true on feeder cables for inverter-fed drives (IFD) for motors and actuators. International standards, such as IEC-60034-18-41 [17], have been developed to qualify random-wound induction motors for use with pulse-width-modulated drives to control motor speed and/or torque. This standard evaluates the motor winding insulation to ensure partial-discharge-free operation in IFD applications, to reduce motor winding failures. These specifications have been developed for motor drive systems that operate in atmospheric pressure environments, not high altitudes.

## 5. Conclusion

The concept of providing overcurrent protection in vehicular power circuits has largely been motivated by a mandate to protect the current carrying conductors. Hence, the protective devices typically operate on the "$i^2t$ principle." The concept of zonal protection has been widely utilized for the utility grid, which has a multiplicity of sources and loads. The new vehicle systems are taking on the characteristics of a "microgrid," with primary generation, energy storage, and regeneration, all tied into a dc distribution system with voltages ranging from 250 to 750 volts. Hence, the vehicular system designers may need to adopt a "zonal" protection philosophy and incorporate smart, fast-acting solid state switching into the protection algorithms controlling dc power distribution units that are designed for overall safety and reliability. The distribution units must take advantage of the unique capabilities of new solid state devices and fault sensors that protect the subsystems and loads, rather than just the current carrying conductors.

To this end, questions must be addressed, such as: What is a practical level of arc fault protection? i.e., limit it to the easily-justified parallel, "bolted" fault condition, or expend resources to add series detection? At what point is there so much protection that it can affect the system cost and operational reliability? In the case of parallel arcs , a significant amount of energy is released in a very short period of time. The $i^2t$ characteristic that is typically used for operation of a circuit breaker may not be sufficiently fast to prevent significant damage. This results in severe demands on the detection and processing method. Work in this area is ongoing and SAE-International is leading the effort to develop dc arc fault detection verification standards for aircraft power applications.

International standards, such as IEC-60034-18-41, have been developed for motor drive systems that operate in atmospheric pressure environments, not the high altitudes that the actuators in future more electric aircraft will experience. Future investigations must be accomplished to evaluate the effects of applying these standard tests on actuator motors under sub-atmospheric conditions, with a view to creating guidelines to accommodate an increasing number of aerospace applications.

## References


[1] Grosjean, D. ; Kasten, D. ; Sebo, S. ; Chen, T. ; Rupp, M. ; Schweickart, D., "Flashover and breakdown characteristics in low pressure environments," Electrical Insulation and Dielectric Phenomena (CEIDP), 2011 Annual Report Conference on, pp. 546 - 549.

[2] MIL-STD-275E, Printed Wiring for Electronic Equipment. April 1984.

[3] DoD Handbook, MIL-HDBK-454B, General Guidelines for Electronic Equipment, Guideline 45, April 2007, MIL-STD-275E, Printed Wiring for Electronic Equipment. April 1984.

[4] NASA JSC-2919, Space Transportation System Orbiter Upgrades Program: Electrical Auxiliary Power Unit (EAPU) Corona Design Guideline, dated June 29, 2000.

[5] UL 60950-1, ISBN 0-7629-1238-3, Information Technology Equipment – Safety – Part 1: General Requirements, second edition, 2007.

[6] IPC-9592, Performance Parameters for Power Conversion Devices, Final Draft, April 2007.

[7] IPC-2221A, Generic Standard on Printed Board Design, IPC - Association Connecting Electronics Industries, May 2003.

[8] IEC-60664-1, Insulation Coordination for Equipment within Low-Voltage Systems – Part 1: Principles, Requirements and Tests, 2002-2006.

[9] IEC-60664-5, Insulation Coordination for Equipment within Low-Voltage Systems – Part 5: A Comprehensive Method for Determining Clearances and Creepage Distances Equal To or Less Than 2 mm, 2003-2008.

[10] J. D. Cobine, Gaseous Conductors (Dover Publications, Inc., New York, 1941 and 1958).

[11] F. A. Maxfield and R. R. Benedict, Theory of Gaseous Conduction and Electronics (McGraw-Hill Book Company, Inc., New York, 1941).

[12] D. F. Grosjean, "Arc fault detection," US Patent Application 20130226479, August 2013.

[13] AS5692/4, *Arc Fault Circuit Breaker - Aircraft, Trip Free, 25 to 35 Amp, Type 1*, SAE International, March 2012.

[14] AS6087, *ARC Fault Interrupter, 270 VDC*, Aerospace Standard, SAE International, work in progress.

[15] IEC60270, *High Voltage Test Techniques—Partial Discharge Measurements,* International Standard, Third Edition, IEC, 2002.

[16] Grosjean, D. F., Schweickart, D. L., Kasten, D. G., Sebo, S. A., and Xin, "Development of procedures for partial discharge measurements at low pressures in air, argon, and helium," *IEEE Trans. Diel. Elect. Insul.*, Vol. 15, No. 6, pp. 546 – 549, 2008.

[17] IEC-60034-18-41, *Partial Discharge Free Electrical Insulation Systems (Type I) Used in Rotating Electrical Machines Fed From Voltage Converters—Qualification and Quality Control Tests*, International Standard, First Edition, 2014.